

On Energy Efficient Scheduling and Load Distribution Based on Renewable Energy for Wireless Mesh Network in Disaster Area

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On Energy Efficient Scheduling and Load Distribution Based on Renewable Energy for Wireless Mesh Network in Disaster Area

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Abstract—In recent years, disasters happened in many places, and resulted in power shortage and communication interruption. The Wireless Mesh Networks (WMNs) constituted by Renewable Energy-enabled Base Station (REBS) is regarded as a powerful solution in post-disaster recovery, for its energy harvesting ability and the ready-made facilities. However, this solution needs to address several challenges such as unstable power supply, limited bandwidth and long-term optimization. In this paper, we focus on the issue of energy efficiency when realizing the maximal network throughput in a period of time, by the combination of energy usage and network data distribution. To this end, we firstly analyze the unique features of REBS and its associated network in disaster area. Then a throughput-maximization problem is proposed in order to figure out the maximal network throughput. Based on the maximal value, we count out the most energy-efficiency result while guaranteeing the maximal network throughput. We formulate the proposed model into a two-stage Mixed-Integer Linear Programming (MILP) problem and solve it by branch-and-bound algorithm. Simulation results demonstrate our considered two-stage energy efficient scheme strikes a balance between network throughput and its associated energy consumption, and outperforms the existing schemes.

I. INTRODUCTION

As the explosive development of the communication devices (i.e., smart phone, handheld devices) over the last decade, the disaster-treating strategy, on the other hand, also need to be put in an important place accordingly. In recent years, disaster events (i.e., earthquake, tornado and tsunami) happened in many places, and had serious effects on our societies. In the field of communication, such disasters will damage the crucial infrastructures, such as the power supply and network facilities. As a direct result, no stable energy is available for the network [1], and the network bandwidth is no longer ample. Besides the above physical damages, to add insult to injury, the users' demands will rise sharply during disaster. According to the statistics in [2], such demands include the mailing applications, telephone calls and so on, and these traffic requirements will eventually cause network congestion. Another requirement in the disaster case is the need for providing a relative long-term network plan, because the affect of disaster will last several days until the network gets recovered. Therefore, in post-disaster case, the network organizer needs to address several challenges such as the power shortage,

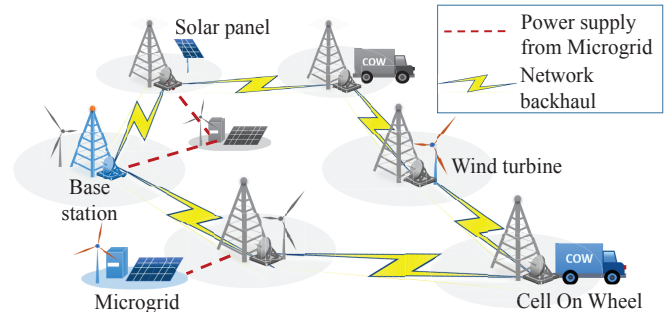


Fig. 1. The structure of renewable energy-enabled base station based wireless mesh network in disaster case.

bandwidth limitation and long-term optimization accordingly.

In order to address the above challenges, extensive efforts have been devoted previously. The Renewable Energy-enabled Base Station (REBS) is a recently emergent structure, which is believed to be an efficient solution toward the energy shortage problem. The REBS is equipped with a renewable energy-enabled facility that could harvest energy from ambient environment. Each REBS has a battery, which could store the renewable energy for the utilization in the upcoming period. For the REBS usage, [3] considered the hybrid energy usage, and [4] considered dynamically controlling the active/inactive status of the REBSs and the user handing off issues. Another energy input could be the Microgrid, which connects the Base Station (BS) and the major power grid. They could harvest the energy, and allocate the harvested energy as well as the energy from power grid to the connected BS. Moreover, the Microgrids could operate independently if they are disconnected to power grid [5] [6]. Due to the differences of location (i.e., sea side, mountain area) and weather condition (i.e., sunny, cloudy), the energy harvesting ability of each REBS is diverse in both temporal and spatial dimensions. To tackle the problem of efficient renewable energy usage for cellular network, more than 10 countries in Europe jointly started the project named Energy Aware Radio and NeTwork TechNologies (EARTH) [7]. Toward Real Energy-efficient Network Design (TREND)

[8] is another project aiming at assessing the energy consumption behavior of current and future telecom infrastructures. Because the destructive effect on the communication links, one could expect that the base stations in the disaster area may lose their original connections to the Internet. Several efforts have been made to provide the Internet connection. For example, the Movable and Deployable Resource Units (MDRUs) [2], and the Cell On Wheel (COW) are the two existing emergency vehicles for Internet provision. With such vehicles, the base stations closed to the edge of the disaster area could connect to the outside network. The residual BSs then operate in a cooperative manner: They formulate a mesh network and use the BS that has the connecting ability as the gateway of the mesh network. In [9], Jacobson *et al.* compared the multiple one-hop paths with multiple hops in cellular system.

In this paper, we consider the scenario in disaster area: We focus on the issue of energy efficiency when realizing the maximal network throughput in a period of time, by the combination of energy usage and network data distribution. We firstly highlight the importance of the combination consideration, due to the relative lack of operating energy and bandwidth in post-disaster case. Then we focus on the throughput maximization within the considered time span. In order to make the result more energy-efficient, we choose the most energy-efficient result among the maximal-throughput result at last. Our proposed solution is a two-stage Mixed Integer Linear Programming (MILP). In the first stage, we use MILP to count out the maximal system throughput that the network could achieve. In the second, we count out the lowest weighted energy consumption with such maximal system throughput. Our scheme achieves high energy efficiency and outperforms the conventional idea, which is demonstrated by the computer-based simulation results.

The remainder of this work is organized as follows. In section II, we retrospect the related research works for WMN using renewable energy. The problem model is demonstrated in section III, and the combination problem is highlighted in this section. To figure out the problem, we propose a two-stage MILP scheme in section IV. In section V, we evaluate the performance of our proposed scheme. Finally, in section VI, we conclude the work in this paper.

II. RELATED WORK

The importance of the renewable energy usage and optimization treatment for the REBS-enabled WMN has drawn the attention of the researchers in recent years. In this section, we mainly concentrate on the works conducted for the WMNs using renewable energy.

For Wireless Mesh Networks (WMNs) with renewable energy facilities, Mostafa *et al.* [10] dealt with the potential congestion in the gateway of WMNs in disaster case, the proposed method could handover some of the mesh routers connected to the congested gateway to the other light-traffic gateways. [11] and [12] combined the energy utilization and route selection together. In [11], Luo *et al.* proposed a min-max-based algorithm so as to minimize the energy consump-

tion while satisfying users' demands. Ngo *et al.* in [12] proposed a spectrum and energy efficiency traffic distribution scheme via multi-path for WMNs in disaster area. Cai *et al.* in [13] considered the stochastic feature of the data traffic demands and the energy input, their work aimed at maximizing the energy sustainability (or minimizing the probability of depletion), with the assumptions that the energy input would follow G/G/1 process, and data input would follow Poisson process respectively.

The above methods are efficient in their unique scenario, however, none of them could satisfy the requirements for the data communication issue in disaster: [10] works only when the energy is sufficient, [11] and [12] are for the one-time-slot optimization, which may result in poor performance in the long run. [13] assumed the energy is the only bottleneck for the performance, which might not be the case for the disaster area in which the network capability is also the bottleneck.

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

In a nutshell, we consider a mesh network constituted by REBSs and Microgrids. As depicted in Fig.1, we assume that there are several REBSs in the disaster area. Each base station is with an energy harvesting facility (i.e., solar panel, wind turbine and so forth) and an energy storage device. The energy harvesting ability is not the same due to the differences of position, time or weather. For each base station, the input energy could be the local energy (from its own energy harvesting device), or non-local energy (from the connected Microgrid). We suppose the energy harvesting profiles could be known beforehand (i.e., by using the weather forecast, history data), and more details of the prediction are shown in [14]. The people in the affected area tend to gather in the sanctuaries, which is covered by a certain REBS. We also assume the traffic demands of each base station is known (i.e., from the number of people in the sanctuary). Among the base stations in disaster area, several of them are repaired by the rescue team, they have enough power and could connect to the outside network with the vehicle-borne facilities. We call such base stations the gateways. The other base stations formulate a mesh-like network via the microwave panel or long-distance WiFi, and connect to the gateways. We consider the orthogonal channels are used among the REBSs, therefore the channel interference between the base stations could be avoided.

There are mainly two functional components that constitute the REBS, namely the energy component and traffic component, as shown in Fig. 2. For each REBS, there are two kinds of input energies, the one is the locally harvested energy that comes from its own energy harvesting facility, the other is the energy from Microgrid. Part of input energy would be used for operation and activated subcarriers, and the extra residual energy will be stored in the battery. The operating energy consumption is a static cost which is made up by the cooling, DC-DC power consumption and so on. The energy consumption introduced by activated subcarriers is determined by the number of subcarriers. On the other hand, the number

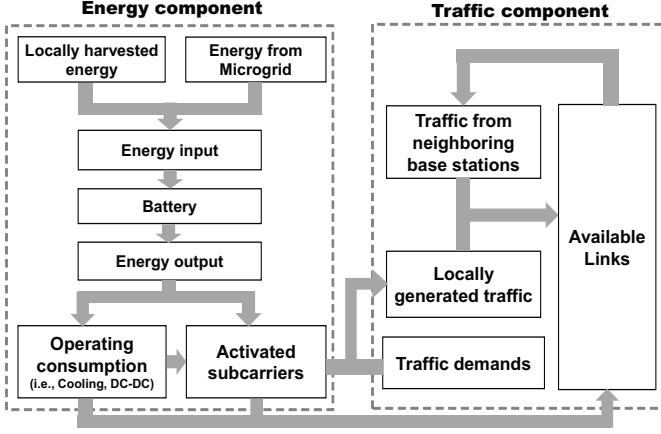


Fig. 2. The two major system components of renewable energy-enabled base station, and their associated working flows inside.

of subcarriers also limits the possible upper bound for uplink traffic of each REBS. Besides the local traffic demands, each REBS needs to relay the traffic sent by its neighbors. It is noticed that there exists the energy consumption of the links between base stations. However, such amount of energy is not significant in comparison with the operating consumption and subcarrier consumption, according to [15]. We omit such consumption in this article.

In this work, we put the effort on getting the most energy-efficient result among the solutions that have the maximum system throughput in a period of time. To this end, we attempt to make use of the energy and traffic profile so as to determine the active/inactive of each REBS, the number of active subcarriers of each active REBS, the transferred path and the amount of traffic on each path. We will describe the detailed problem in the next subsection.

B. Problem Formulation

The time-slotted system is included in our consideration. We sample the consecutive time into discrete points, and each point represents a certain period of time. Let interval $[0, T_0)$ denote the considered time span, and we divide such interval into T slots with equal length t_0 . Hence the original interval is transferred into discrete time samples $\mathcal{T} = \{[0, t_0), [t_0, 2t_0), \dots, [(T-1)t_0, Tt_0)\}$, and t_i represents the i -th time slots (i.e., t_2 is $[t_0, 2t_0)$). We suppose the traffic demands and energy harvesting ability of each base station is stable during t_i .

We assume that the gateway could send all the input traffic to the outside network. We use $\mathcal{G} = \{g_1, g_2, \dots, g_G\}$ to represent the set of gateways, where $|\mathcal{G}| = G$. In addition, we assume that there are N affected base stations in the disaster area, and \mathcal{N} ($\mathcal{N} = \{n_1, n_2, \dots, n_N\}$) is the set of these base stations, where $|\mathcal{N}| = N$. These base stations formulate a mesh-like network after disaster and $\mathcal{G} \subset \mathcal{N}$. Let $c_{(n_j, n_k)}(t_i)$ denote the link capacity of (n_j, n_k) that connects n_j and n_k in t_i . The value of $c_{(n_j, n_k)}(t_i)$ is determined by two factors: The first is the active/inactive status of n_j and n_k . We use $\rho_{n_j}(t_i)$

to denote the status of n_j in t_i :

$$\rho_{n_j}(t_i) = \begin{cases} 1, & \text{if } n_j \text{ is active in } t_i \\ 0, & \text{otherwise} \end{cases}. \quad (1)$$

When n_j is inactive in t_i ($\rho_{n_j}(t_i) = 0$), it will shut down the functional components and stop operating. The second is the original link capacity between n_j and n_k , which is $c_{n_j}^{n_k}$. Therefore, $c_{(n_j, n_k)}(t_i)$ should be as follows:

$$c_{(n_j, n_k)}(t_i) \leq c_{n_j}^{n_k} \cdot \rho_{n_j}(t_i), \quad (2)$$

$$c_{(n_j, n_k)}(t_i) \leq c_{n_k}^{n_j} \cdot \rho_{n_k}(t_i). \quad (3)$$

C. Power Consumption Model

In general, the power consumption of base station n_j in t_i does not only depend on $\rho_{n_j}(t_i)$, but also on the activated subcarriers for uplink when $\rho_{n_j}(t_i) = 1$. The more subcarriers are used to operate, the more power it will consume and more uplink bandwidth it could provide [16]. Let $P_{n_i}(t_i)$ denote the total power consumed by n_i in t_i , $s_{n_i}(t_i)$ ($s_{n_j}(t_i) \in \mathbb{Z}^+$) denote the number of activated subcarriers in time slot t_i , e_s denote the power requirement of each subcarrier, and e_0 denote the operating energy consumption (i.e., cooling system, baseband), then their relationship is as follows:

$$P_{n_j}(t_i) = [(s_{n_j}(t_i) \cdot e_s) + e_0] \cdot \rho_{n_j}(t_i), \quad (4)$$

and $s_{n_j}(t_i)$ should be less than the maximal number of subcarriers S :

$$s_{n_j}(t_i) \leq S. \quad (5)$$

For each base station, there are two kinds of input energy, the one is the energy from their own energy harvesting facilities, the other is from the available Microgrids in the network. Denote $\mathcal{M} = \{m_1, m_2, \dots, m_M\}$ as the set of Microgrids, and $|\mathcal{M}| = M$ ($M \in \mathbb{Z}^+$). Each m_k connects to several base stations, we denote the set of associated base stations of m_k by $M^{(m_k)} = \{n_1^{m_k}, n_2^{m_k}, \dots\}$ ($n_i^{m_k} \in \mathcal{N}$). Suppose the energy that m_k could harvest during t_i is $h^{m_k}(t_i)$, and the amount of power that is allocated to n_j is $h_{n_j}^{m_k}(t_i)$. For the base station that does not connect to m_k , the received energy from m_k is always 0. We have the following equation:

$$\sum_{n_j \in M^{(m_k)}} h_{n_j}^{m_k}(t_i) \leq h^{m_k}(t_i). \quad (6)$$

The base stations could receive energy from its local energy facility as well. The average local harvested energy of n_j in t_i is $h'_{n_j}(t_i)$. Hence during t_i , the available energy for n_j is

$$H_{n_j}(t_i) = \sum_{m_k \in \mathcal{M}} h_{n_j}^{m_k}(t_i) + h'_{n_j}(t_i). \quad (7)$$

Equation (7) means that the total received energy of n_j in t_i is the sum of the non-local energy and local energy. Base station uses battery to store the harvested energy. We consider the REBS with a finite capacity battery, which could be recharged repeatedly. The battery capacity for n_j is $B_{n_j}^0$. Let $B_{n_j}(t_i)$

denote the residual energy of n_j 's battery at the beginning of t_i , then it could be determined by the following equations:

$$B_{n_j}^0 \geq B_{n_j}(t_i) \geq 0, \quad (8)$$

$$B_{n_j}(t_i) = B_{n_j}(t_{i-1}) + H_{n_j}(t_{i-1}) - P_{n_j}(t_{i-1}). \quad (9)$$

Equation (9) means that the residual energy of n_j in t_i is determined by the initial residual energy, energy input and energy consumption in t_i . Similarly, suppose the battery capacity of m_k is $B_{m_k}^0$, the residual energy of the battery of m_k at the beginning of t_i should be constrained by the following equations:

$$B_{m_k}^0 \geq B_{m_k}(t_i) \geq 0, \quad (10)$$

$$B_{m_k}(t_i) = B_{m_k}(t_{i-1}) + h^{m_k}(t_{i-1}) - \sum_{n_j \in \mathcal{M}^{(m_k)}} h_{n_j}^{m_k}(t_{i-1}). \quad (11)$$

D. Traffic Model

We assume the traffic transmission request of n_j in t_i is $d_{n_j}(t_i)$. However, not all the request could be fulfilled due to the bandwidth limitation of uplink. Such bandwidth is determined by $s_{n_j}(t_i)$ in (4), and r_0 , which is the achievable transmission rate when a subcarrier is active. Suppose the actually allowed traffic sent by n_j in t_i is $f_{n_j}(t_i)$, and it should satisfy the following constraints:

$$f_{n_j}(t_i) \leq \rho_{n_j}(t_i) \cdot s_{n_j}(t_i) \cdot r_0, \quad (12)$$

$$f_{n_j}(t_i) \leq d_{n_j}(t_i). \quad (13)$$

Each base station could not only collect data from its own associated users, but also act as a relay that could transfer the data sent from other base stations. Denote the traffic from n_l , and sent via link (n_j, n_k) in t_i by $f_{n_l}^{(n_j, n_k)}(t_i)$. The total traffic via link (n_j, n_k) , should be less than its capacity:

$$\sum_{n_l \in \mathcal{N}} f_{n_l}^{(n_j, n_k)}(t_i) \leq c_{(n_j, n_k)}(t_i). \quad (14)$$

Besides satisfying the link capacity constraint, n_j should have the ability to send all the traffic that going through n_j (including the traffic from itself and others). Such relationships could be denoted from a flow-conservation point of view as follows:

$$\sum_{v \in \mathcal{N}, u \in \mathcal{N} - \{n_j\} - \mathcal{G}} f_{n_j}^{(u, v)}(t_i) = 0, \quad (15)$$

$$f_{n_j}^{(u, v)}(t_i) = -f_{n_j}^{(v, u)}(t_i), \quad (16)$$

$$f_{n_j}(t_i) = \sum_{u \in \mathcal{N} - \{n_j\}} f_{n_j}^{(n_j, u)}(t_i). \quad (17)$$

Constraints (15) and (16) guarantee that if base station u is the relay of the flow generated by n_j (u is neither the source of the flow nor the gateway), then the flow should be completely sent to its neighbors. Constraint (17) ensures that the n_j has the enough bandwidth to transfer the local data to its neighbors.

Let $U(t_i)$ denote the total system utility during t_i , which is the sum of the traffic that flows through the gateway.

$U(\vec{s}, \vec{\rho}, \vec{f}, \vec{h})$ represents the total system throughput in \mathcal{T} with the subcarrier decision \vec{s} , active status $\vec{\rho}$, traffic distribution decision \vec{f} and energy allocating decision \vec{h} . Since all the generated traffic could be sent to the gateway due to constraints (15) to (17), then

$$U(\vec{s}, \vec{\rho}, \vec{f}, \vec{h}) = \sum_{t_i \in \mathcal{T}} U(t_i) = \sum_{t_i \in \mathcal{T}} \sum_{j \in \mathcal{N}} f_{n_j}(t_i). \quad (18)$$

Our goal is to find the result that has the minimum weighted energy consumption among the results of the maximum system utility in the time period $[0, T_0)$. This aim has an important meaning in disasters: Firstly, the maximum throughput could satisfy as much as data traffic demand. Secondly, reducing the energy consumption with considering the energy harvesting ability helps to enhance the sustainability of network. Suppose \mathcal{L} represents the set that contains the maximal system utility solutions, therefore, the objective could be denoted as follows:

$$\text{P1 : } \min w(\vec{s}, \vec{\rho}, \vec{f}, \vec{h}), \quad (19)$$

where

$$w(\vec{s}, \vec{\rho}, \vec{f}, \vec{h}) = \sum_{n_j \in \mathcal{N}} \left(\frac{\sum_{t_i \in \mathcal{T}} (P_{n_j}(t_i) - \sum_{m_k \in \mathcal{M}} h_{n_j}^{m_k}(t_i))}{\sum_{t_i \in \mathcal{T}} h'_{n_j}(t_i)} \right) + \sum_{m_k \in \mathcal{M}} \left(\frac{\sum_{t_i \in \mathcal{T}} \sum_{n_j \in \mathcal{M}^{(m_k)}} h_{n_j}^{m_k}(t_i)}{\sum_{t_i \in \mathcal{T}} h^{m_k}(t_i)} \right), \quad (20)$$

the domain of definition is \mathcal{L} ($D(w) = \mathcal{L}$), where

$$\mathcal{L} = \{ \mathbf{a} = (\vec{s}, \vec{\rho}, \vec{f}, \vec{h}) \mid U(\mathbf{a}) \geq U(\mathbf{b}), \text{ where } \mathbf{a} - \mathbf{b} \neq \mathbf{0}, \text{ and } \mathbf{a}, \forall \mathbf{b} \in \text{dom} \}. \quad (21)$$

From (20), the weighted energy consumption is constituted by two parts. The first part is the sum of weighted energy consumed by each REBS. For each REBS, such energy is the ratio of local energy consumption (equals to the actual energy consumption subtracts the energy from Microgrids) to the local energy harvesting ability. The second part is the sum of weighted energy consumed by Microgrid. Such weighted energy is the total distributed energy divided by total harvested energy. With the result of P1, the maximum system utility could be achieved, and the system could support the data traffic demand as much as possible; with the least weighted energy consumption, we get the maximum throughput with considering both of the energy consumption and energy harvesting ability of the REBSs.

IV. PROPOSED TWO-STAGE ENERGY EFFICIENT SCHEME

A. Remove the non-linear constraints

On the surface, problem P1 contains nonlinear constraints (i.e., constraint (4), (12)), and therefore seems to be a non-linear optimization problem. Actually, a simple transformation could change the form into linear one. Here we introduce an extra variable $\delta_{n_j}(t_i)$, which is equal to

$$\delta_{n_j}(t_i) = s_{n_j}(t_i) \cdot \rho_{n_j}(t_i), \quad (22)$$

and we have the following relationship:

$$\delta_{n_j}(t_i) = s_{n_j}(t_i) \cdot \rho_{n_j}(t_i) \leq S \cdot (\rho_{n_j}(t_i))^2 = S \cdot \rho_{n_j}(t_i). \quad (23)$$

This is because $s_{n_j}(t_i)/S \leq \rho_{n_j}(t_i)$, then $s_{n_j}(t_i) \leq S \cdot \rho_{n_j}(t_i)$. Since $\rho_{n_j}(t_i) \in \{0, 1\}$ and $(\rho_{n_j}(t_i))^2 = \rho_{n_j}(t_i)$, and $P_{n_j}(t_i)$ that in equation (4) and $f_{n_j}(t_i)$ that in equation (12) could be transformed as (24) and (25) respectively:

$$P_{n_j}(t_i) = (\rho_{n_j}(t_i) \cdot e_0) + e_s \cdot \delta_{n_j}(t_i), \quad (24)$$

$$f_{n_j}(t_i) \leq \delta_{n_j}(t_i) \cdot r_0. \quad (25)$$

Therefore, with $\delta_{n_j}(t_i)$, P1 is then transformed into the problem with linear and integer constraints.

B. Proposed Two-stage Energy Efficient Scheme

In general, the way that we use to solve P1 contains two stages. The first stage is to count out the maximum system throughput in the given time period $[0, T_0)$. The objective and related constraints are as follows:

$$\text{P2: } \tau = \mathbf{max} \sum_{t_i \in \mathcal{T}} U(t_i), \quad (26)$$

subject to constraints (1)-(3), (5)-(11), (13)-(18) and (24)-(25). In the main, P2 (Eq. (26)) is a Mixed Integer Linear Programming (MILP) and could be efficiently attacked by many existing solutions (i.e., branch and bound, linear relax). After figuring out the result, τ records the maximal achievable system utility.

In the second stage, we use τ as a constraint for the P3, the objective and related constraints are as follows:

$$\text{P3: } \mathbf{min} w(\vec{s}, \vec{\rho}, \vec{f}, \vec{h}), \quad (27)$$

subject to

$$\sum_{t_i \in \mathcal{T}} \sum_{j \in \mathcal{N}} f_{n_j}(t_i) = \tau, \quad (28)$$

as well as the constraints (1)-(3), (5)-(11), (13)-(18) and (24)-(25), where $w(\vec{s}, \vec{\rho}, \vec{f}, \vec{h})$ is same as (20). Because the objective is a linear combination of the variables, and the constraints are either linear or integer, therefore, it is also an MILP problem.

The result of P3 in (27) is the same as the result of P1 in (19). This is because constraint (28) guarantees its result has the maximum system utility (equals to τ), and the objective in (27) is to count out the minimum weighted power consumption, which is same as (19). The major steps of the proposed two-stage energy efficient scheme are as Algorithm 1 shows. In Algorithm 1, line 1 to 9 is the first stage that figures out the maximal system throughput defined in P2. The algorithm firstly relaxes the MILP problem (P2) into LP one (P2'), then counts out the results and related environments, and stores them into \bar{O} and vector \mathbf{u}' respectively. If \mathbf{u}' exactly satisfies the integer constraints, then \bar{O} is the maximal result, else we rely on *BranchBound* procedure to further divide the problem. *BranchBound* eventually returns the maximal value and \underline{Q}^* represents such value. In the second stage, we use \underline{Q}^* as a new constraint to problem P3. Similarly, P3 is relaxed into P3', then an LP problem is formulated. If the

Algorithm 1: Two-stage Energy Efficient Scheme

Input: Network topology information: $\mathcal{N}, \mathcal{G}, \mathcal{M}, c_{n_j}^{m_k}$.

Energy related information: $e_s, e_0, h_{n_j}^{m_k}(t_i), h^{m_k}(t_i)$.

Traffic related information: $d_{n_j}(t_i) r_0$.

Output: $(\vec{s}, \vec{\rho}, \vec{f}, \vec{h})$ for problem P3.

- 1 Relax the integer constraints of $\vec{\rho}$ and \vec{s} into linear ones, then the problem P2 is transformed into P2';
 - 2 Solve P2' by linear programming, let \bar{O} record the result and $\mathbf{u}' = (\vec{s}', \vec{\rho}', \vec{f}', \vec{h}')$ is the associated variables;
 - 3 **if** \mathbf{u} satisfies integer constraints of P2 **then**
 - 4 $\underline{Q}^* = \bar{O}$;
 - 5 **else**
 - 6 $\underline{Q} = 0$;
 - 7 $Cons =$ the constraints of P2;
 - 8 Choose one relaxed constraint x that does not follow the constraints of P2. Let χ denote the value of x ;
 - 9 $(\underline{Q}^*, \bar{O}) = \text{BranchBound}(Cons, x, \chi, \text{P2}, \underline{Q}, \bar{O})$;
 - 10 Let \underline{Q}^* be the τ in constraint (28), and relax the integer constraints of $\vec{\rho}$ and \vec{s} into linear ones, then use P3' to represent the transformed problem;
 - 11 Solve P3' by linear programming, let \bar{O} record the result and $\mathbf{u} = (\vec{s}', \vec{\rho}', \vec{f}', \vec{h}')$ is the associated variables;
 - 12 **if** \mathbf{u} satisfies integer constraints of P3 **then**
 - 13 **return** \mathbf{u}' ;
 - 14 **else**
 - 15 $\underline{Q} = 0$;
 - 16 $Cons =$ the constraints of P3;
 - 17 Choose one relaxed constraint x that does not follow the constraints of P3. Let χ denote the value of x ;
 - 18 $(\underline{Q}^*, \bar{O}) = \text{BranchBound}(Cons, x, \chi, \text{P3}, \underline{Q}, \bar{O})$;
 - 19 **return** the strategy that achieves \underline{Q}^* .
-

result of P3' just conforms the integer requirement, then the algorithm returns \mathbf{u}' which records the associated variables. Otherwise the algorithm will choose an integer variable and use *BranchBound* procedure to count out the result. The core idea of *BranchBound* is to divide the solution space into several sub-spaces, and gradually shrink the searching by removing the non-necessary branches. In *BranchBound*, it accomplishes the mentioned procedures in a recursive manner. The detail procedure of *BranchBound* is shown in Appendix.

V. PERFORMANCE EVALUATION

In this section, we examine the performance of the proposed scheme through the computer-based simulations. Three schemes are compared in this section: Proposed two-stage energy efficient scheme (Energy-efficient throughput maximization), the scheme that only solves the problem P2 (Throughput-maximization only), and the naive scheme (Naive), which would be introduced later. The considered simulation parameters are listed in table I. As table I shows, we assume each time slot t_i represents 1 hour. We consider the scenario

TABLE I
EXPERIMENTAL PARAMETERS

Parameter	Value
t_i	1 hour
The number of considered time slots (T)	10
Number of REBSs (N)	10
Number of Microgrids (M)	3
Bandwidth of the Backhaul link ($C_{n_j}^{n_k}$)	80 to 300Mbps
Operating power consumption (e_0)	712.2W
Power consumption per subcarrier (e_s)	1.06W
Number of subcarriers S	600
Battery capacity of REBS $B_{n_j}^0$	2000W
Rate of subcarriers r_0	0.5Mbps

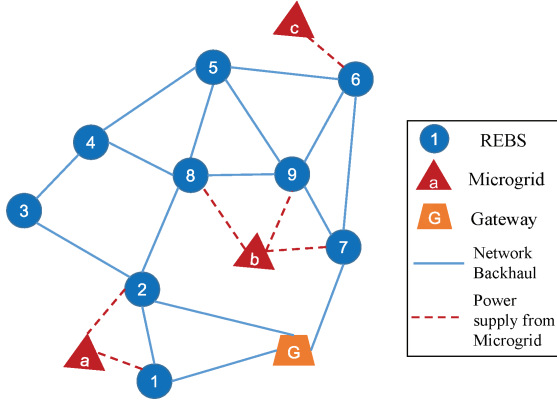


Fig. 3. System topology used in the performance evaluation.

with 10 Renewable Energy-enabled Base Stations ($N = 10$). Each REBS connects to its neighbors by microwave panel or long distance WiFi. The bandwidth of the link connecting two neighboring REBS is randomly chosen from 80Mbps to 300Mbps. We assume these REBSs in this section are macro base stations. According to the measurement in [15], we set the operating power consumption of each macro base station $e_0 = 712.2W$, $e_s = 1.06W$ and the number of subcarriers is $S = 600$. The battery capacity is set as 4kW. In this simulation, every 60 subcarriers is regarded as an active unit, that means, these 60 subcarriers are simultaneously active or inactive.

In the remainder of this section, we mainly investigate our proposed two-stage scheme by two performance metrics, namely the system throughput and the energy efficiency. The topology of the network is shown in Fig. 3.

The naive idea represents the operation strategy for the REBS in non-disaster scenario. The core idea of the naive one is to keep the base station operating so long as it has enough power. For the local traffic demands, the naive idea encourages the base station to send all of them. If the local energy could not support the local traffic demands, then the base station sends its energy request to the connected Microgrids. The Microgrids collect all the energy requirements from their associated base stations, if all the requirements could be fulfilled, then the Microgrids send the amount of required energy to each connected base station. Otherwise all the requirements will be sorted in ascending order, and

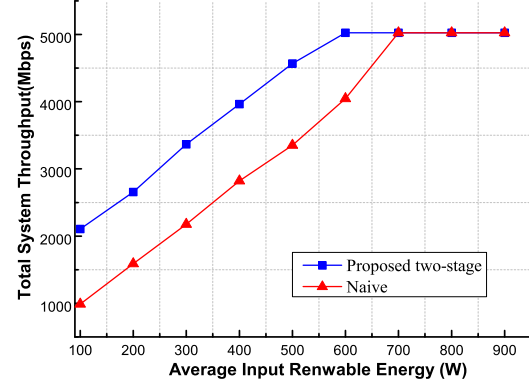


Fig. 4. The effect of average input renewable energy on system throughput of the proposed scheme and naive scheme.

Microgrids will firstly transfer the required energy to the least-demand base station, then to the second one, until it could not send the energy any more. After determining the working status of each base station, the scheme makes use of Max-Flow algorithm to find out the path and related traffic distribution.

A. Effect of Total Available Energy on System Throughput and Energy Consumption

In this simulation, we try to vary the input renewable energy. For each base station, the renewable energy input in each time slot is uniformly and randomly chosen from interval $[0.5 * \text{average value}, 1.5 * \text{average value}]$. The traffic demand for each base station in each time slot is uniformly and randomly chosen from the interval $[40\text{Mbps}, 100\text{Mbps}]$. Other experiment parameters are set as table I.

Fig. 4 illustrates the change of the system throughput, with the average input rate of the renewable energy of each REBS and Microgrids. As Fig. 4 shows, the total system throughput is directly proportional to the average harvested energy. This is because as more energy could be used for the network, comparatively longer operating time and more active subcarriers could be supported for each base station, then more traffic could be delivered to the destination. The proposed scheme has better system throughput, and the rationale is twofold: Firstly, the strategy without considering the working status of neighbor REBSs will lead to an unsatisfied result. Secondly, the current optimal throughput cannot pave the road for future optimization. If the REBS consumes too much energy in current time, the lack of energy in future will potentially reduce its throughput. It is worthwhile to note that when the input renewable energy is more than 700W per each REBS, the throughput keeps at the peak point for the two schemes, this is because before 700W, the bottleneck of the network is the input energy, and after 700W, the input traffic and network capacity become the bottleneck.

Fig. 5 demonstrates the effect of the average input renewable energy to the consumed power per megabit. This metric

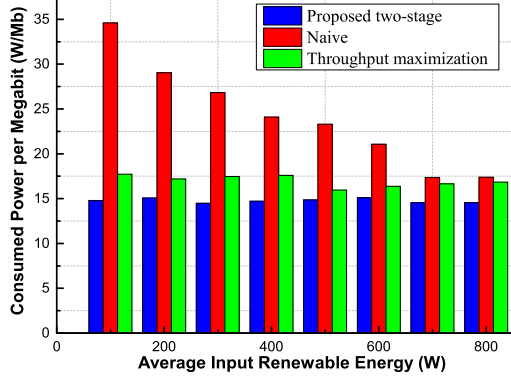


Fig. 5. The effect of average input renewable energy on consumed power per megabit of the proposed scheme, naive scheme and throughput maximization scheme.

represents how well the energy is used to transfer data. From the figure, we could see the proposed two-stage scheme has a lower energy consumption for each piece of data, and there is a clear difference between the proposed scheme and other schemes. In general, the consumed power per bit varies inversely with input renewable energy for the naive idea. This is because more available power enables more REBS keep operating, and guarantees all the transmission. On the contrary, the proposed scheme is free of the effect of input energy.

B. Effect of Total traffic demands on System Throughput and Energy Consumption

In this simulation, we consider the traffic demands as the variable. The traffic demands for each base station in each time slot is uniformly and randomly chosen from the interval $[0.5 \times \text{average value}, 1.5 \times \text{average value}]$. The renewable energy input for each base station in each time slot is also uniformly and randomly chosen from interval $[100W, 300W]$. Other experiment parameters are set as table I.

From Fig. 6, it could be known that as the traffic demand grows, the system throughput increases accordingly. However, after reaching to a certain level, the system throughput of the two schemes keeps stably. The reason behind such phenomenon is same as the previous section: Before such level, the available energy for system is relative ample, the only bottleneck for system throughput is the input traffic. Then there is a proportional relationship between the total system throughput and input traffic. When the traffic demands is higher than this level, the harvested energy will be not enough to support the traffic demands, and the energy gradually becomes bottleneck. Besides energy, the network capacity is also the factor that impedes the improvement of the total system throughput. The system throughput of the proposed scheme is well ahead of the naive one when the input energy is not enough (average energy input is 200W), owing to the fact that the proposed scheme saves current energy input for future use.

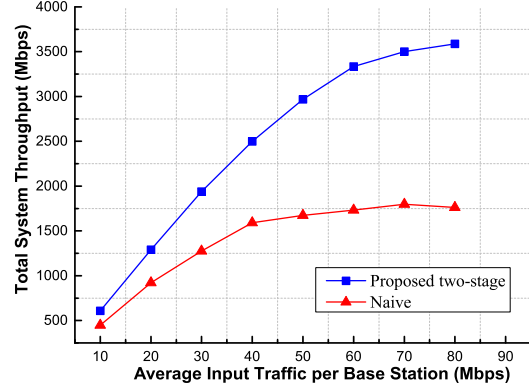


Fig. 6. The effect of average input traffic per base station on total system throughput of the proposed scheme and naive scheme.

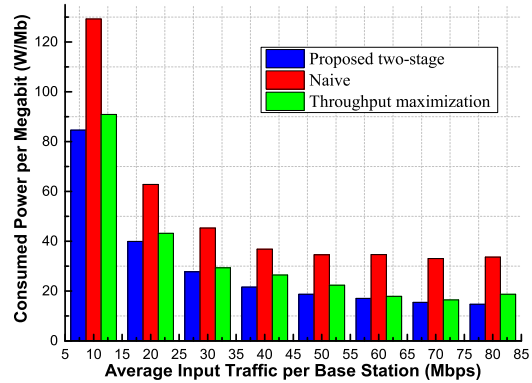


Fig. 7. The effect of average input traffic per base station on consumed power per megabit of the proposed scheme, naive scheme and throughput maximization scheme

Fig. 7 shows the comparison of consumed power per megabit of the proposed two-stage scheme, the throughput maximization scheme and the naive idea. Similar to the previous subsection, the performance gap between the two schemes is clear to see. This is because the proposed two-stage scheme tries to achieve the maximal throughput (the first stage) with a low energy consumption (the second stage). The naive idea implements a more aggressive energy consumption strategy, and results in more energy consumption.

VI. CONCLUSION

In this paper, we consider the energy-efficient throughput-optimization problem for the Wireless Mesh Network (WMN) composed of Renewable Energy-enabled Base Stations (REBSs) and affected by disaster in a given period of time. We propose a scheme that takes the energy-harvesting profile into consideration to achieve the energy-efficient result. We firstly analyze the unique features of REBS and its associated

network in disaster area. Then a throughput-maximization problem is proposed in order to count out the maximal network throughput. Based on the maximal value, we count out the most energy-efficient result while guaranteeing the maximal network throughput. We formulate the proposed model into a two-stage Mixed-Integer Linear Programming (MILP) problem and solve the problem by branch-and-bound algorithm. The numerical results show that our proposed two-stage energy efficient scheme could achieve high system throughput, and keep a low weighted energy consumption.

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APPENDIX

The procedure of *BranchBound* in pseudocode is shown as follows.

Algorithm 2: BranchBound

Input: Current constraints $Cons$, relaxed variable x , the value of x is χ , current considered problem $Prob$, lower bound \underline{Q} and upper bound \overline{O} .

Output: \underline{Q} and \overline{O} .

- 1 Solve $Prob$ with relaxed $Cons$, and $x \leq \lfloor \chi \rfloor$. Let τ_1 denote the result and \mathbf{u}'_1 is the associated variables;
- 2 Solve $Prob$ with relaxed $Cons$, and $x \geq \lfloor \chi \rfloor + 1$. Let τ_2 denote the result and \mathbf{u}'_2 is the associated variables;
- 3 **if** $\tau_1 \leq \underline{Q}$ or $\mathbf{u}'_1 = \emptyset$ **then**
- 4 **if** $\tau_2 \leq \underline{Q}$ or $\mathbf{u}'_2 = \emptyset$ **then**
- 5 **return**($\underline{Q}, \overline{O}$);
- 6 **else**
- 7 **if** \mathbf{u}'_2 satisfies constraints of $Prob$ **then**
- 8 **return**(τ_2, \overline{O});
- 9 **else**
- 10 Choose a relaxed constraint x_2 in \mathbf{u}'_2 that does not follow the constraints of $Prob$. Let χ_2 denote the value of x_2 in \mathbf{u}'_2 ;
- 11 **return**($BranchBound(Cons \cup \{x \geq \lfloor \chi \rfloor + 1\}, x_2, \chi_2, Prob, \underline{Q}, \overline{O})$);
- 12 **else**
- 13 **if** $\tau_2 \leq \underline{Q}$ or $\mathbf{u}'_2 = \emptyset$ **then**
- 14 **if** \mathbf{u}'_1 satisfies constraints of $Prob$ **then**
- 15 **return**(τ_1, \overline{O});
- 16 **else**
- 17 Choose a relaxed constraint x_1 in \mathbf{u}'_1 that does not follow the constraints of $Prob$. Let χ_1 denote the value of x_1 in \mathbf{u}'_1 ;
- 18 **return**($BranchBound(Cons \cup \{x \leq \lfloor \chi \rfloor\}, x_1, \chi_1, Prob, \underline{Q}, \overline{O})$);
- 19 **if** $\tau_1 \geq \tau_2$ and \mathbf{u}'_1 satisfies constraints of $Prob$ **then**
- 20 **return**(τ_1, \overline{O});
- 21 **if** $\tau_2 \geq \tau_1$ and \mathbf{u}'_2 satisfies constraints of $Prob$ **then**
- 22 **return**(τ_2, \overline{O});
- 23 Choose a relaxed constraint x_1, x_2 that does not follow the constraints of $Prob$, let χ_1, χ_2 denote their values respectively;
- 24 $(\tau_{temp1}, \overline{O}_{temp1}) = BranchBound(Cons \cup \{x \leq \lfloor \chi \rfloor\}, x_1, \chi_1, Prob, \underline{Q}, \overline{O})$;
- 25 $(\tau_{temp2}, \overline{O}_{temp2}) = BranchBound(Cons \cup \{x \geq \lfloor \chi \rfloor + 1\}, x_2, \chi_2, Prob, \underline{Q}, \overline{O})$;
- 26 **return** $\max(\tau_{temp1}, \tau_{temp2})$ and associated \overline{O}_{temp} ;
